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AN EXPERIMENTAL STUDY ON THE TWO-PARAMETER CRACK TIP FIELD

by

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ABSTRACT

J-integral values were determined directly from the measured orthogonal displacement fields surrounding a crack in 2024-0, 2024-T3, 2091-T3 and 5052-H32 aluminum alloy SEN and cruciform specimens of 0.8 mm thickness. These J-values were then used to compute the crack tip displacements associated with the HRR field. The second order displacement component in the two-parameter, J-T and the more general J-Q ductile fracture theories was obtained by subtracting the HRR displacement from the measured crack tip displacement. This second order displacement component in the direction parallel to the crack was an order larger than the corresponding component perpendicular to the crack as predicted by the J-Q theory but not by the J-T theory. The negative slope of the log-log plots of the two orthogonal, second order displacement components with respect to the radial distance, however, suggests a strain singularity higher than that of the HRR strain singularity. The basic postulate of the asymptotic expansion of crack tip stress is violated and thus neither the J-T nor the J-Q theory can be a valid criterion in elastic-plastic fracture mechanics.

KEYWORDS: elastic-plastic fracture mechanics, J-integral, J-Q theory, J-T theory, HRR field, moire interferometry, crack tip displacements.

INTRODUCTION

With the development of an experimental procedure to record simultaneously two orthogonal surface displacements in a fracture specimen [1], it became possible to measure, for the first time, the J-integral directly without resorting to theoretical and numerical solutions, many of which are based on simplifying assumptions. One of the intriguing consequence was that the J-integral values thus determined [2] differed substantially with previously published solutions [3] in the presence of large scale yielding. Since net section yielding was a prerequisite [4] for developing these solutions, such discrepancy casts doubt on the modeling procedure used in the sanctimonious elastic-plastic finite element analyses (FEM) in these studies.[1] Another conclusion derived from the experimental study was that the J-integral is not path independent after a relatively short stable crack growth of about 1 mm [5,6] and differs by as much as 40 percent in the presence of a 6 mm crack extension [7]. While the latter conclusion was not unexpected from the definition of the J-integral, previous FEM analysis [8] showed that such difference could be about 10 percent which is approximately one third of that measured in [6]. From the practical view point, the extensive practices of using far-field J-integral values to correlate fatigue crack extension and stable crack growth are therefore inherently flawed since the J-integral is not path independent even under moderate crack extension of about 3 to 5 mm.

The experimental results of [2,5,6] also showed that the HRR displacement fields [9], which were computed by using the measured J-integral values and the numerically determined system coefficient [10], did not agree with the measured crack tip displacement field during the early part of plastic yielding. This finding triggered a series of numerical [11,12,13] and experimental [14,15] studies "in search of an HRR field" where the indications are that the HRR field could exist in the very vicinity of the crack tip, say within 1 mm, which is beyond the sensitivity of the experimental technique employed in [2,5,6]. This severe geometric restriction placed on the HRR field negates its role in continuum theory of fracture mechanics which is ineffective in the micromechanics regime governed by crystalline anisotropy and inhomogeneity. Since the J-integral is physically interpreted as the strength of the HRR field, the lack of the HRR field at the crack tip renders the J-integral without a physical foundation.

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1 J.C. Newman, Jr. attributes the errors to the small deformation analysis used in [3,4].

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Although the above experimental investigation [2,5,6] was confined to thin aluminum specimens of 0.8 mm thickness, the SEN cruciform specimen used in part of the studies represented a highly constrained geometry where the one parameter characterization by the J-integral was deemed valid. For a low-constrained specimen geometry, the two-parameter characterizations by the J-T theory [16] or the more generalized J-Q theory [17,18] nave been promoted to resolve the difficulties associated with the low constraint. The T and the Q in these characterizations are the second order term in the asymptotic crack tip stress state where T is a constant[1] and Q varies with the radial distance, r, from the crack tip. While numerical analysis based on the J-T and the J-Q theories have been made and an ASTM symposium on this subject[2] has been held, no direct experimental validation of the J-T and J-Q theories have been made to date.

The purpose of this paper is to report on our preliminary experimental findings regarding the J-T and J-Q theories in elastic-plastic fracture mechanics.

TWO PARAMETER CRACK TIP FIELD

The two parameter crack tip field which was proposed by Betegon and Hancock [16] is a special case of that of Sharma and Aravas [18] and thus only the latter will be reviewed here. Sharma and Aravas considered a two dimensional elastic-plastic material which can be described by the J_2 deformation theory and the following Ramberg-Osgood uniaxial stress-strain relation:

$$\varepsilon_{ij} = \frac{1+\nu}{E}\, s_{ij} + \frac{1-2\nu}{3E}\, \sigma_{kk}\delta_{ij} + \frac{3}{2}\,\alpha\varepsilon_o \left(\frac{\sigma_e}{\sigma_o}\right)^{n-1} \frac{s_{ij}}{\sigma_o} \tag{1}$$

where i, j = 1 or 2 which corresponds to a Cartesian coordinate system with axes parallel or perpendicular to the crack, respectively. The existence of the following asymptotic expansion of the crack tip solution was postulated and represented in terms of the Mises equivalent stress as

$$\frac{\sigma_e(r,\theta)}{\sigma_o} = r^s\sigma_e^{(o)}(\theta) + r^t\,\sigma_e^{(1)}(\theta) + \cdots \qquad \text{as } r \to 0 \tag{2}$$

1 T was designated as the remote stress component by Irwin in 1958 [19].

2 ASTM Symposium on Constraint Effects in Fracture, May 8-9, 1991.

$$\sigma_e^{(0)} = \left(\frac{3}{2} s_{ij}^{(0)} s_{ij}^{(0)}\right)^{1/2} \quad \text{and} \quad \sigma_e^{(1)} = \frac{3}{2} \frac{s_{ij}^{(0)} s_{ij}^{(1)}}{\sigma_e^{(0)}} \tag{3}$$

A J-integral argument is then used to determine the leading order exponent of s = -1/(n+1) and to no surprise the HRR crack tip field [9,20] is recovered from the first term in Equation (2). The order of magnitude of the second term in Equation (2) depends on second exponent t. In particular, when t = 0, the celebrated T stress component of [16] is recovered.

Using the asymptotic homogeneous boundary conditions, the first two terms in Equation (2) can be obtained if t < (n - 2)/(n + 1) which implies, as per [18], that $\sigma^{(1)}$ and $u^{(1)}$can be determined to within a multicative constant and their values depend on the far field loading. This far field influence, which is consistent with Irwin's prediction of 1958 [19], was also studied independently by O'Dowd and Shih for fracture under large scale yielding [21,22].

The strain and the displacement components, which are relevant to this experimental study, can be represented in a nondimensional form as $r \to 0$,

$$\frac{\varepsilon(r,\theta)}{\alpha\varepsilon_0} = \left(\frac{J}{\alpha\varepsilon_0\sigma_0 I_n r}\right)^{n/(n+1)} \tilde{\varepsilon}^{(0)}(\theta) + \frac{Q}{(J/\sigma_0)^t}\left(\frac{J}{\alpha\varepsilon_0\sigma_0 I_n}\right)^{(n-1)/(n+1)} r^{s(n-1)+t}\tilde{\varepsilon}^{(1)}(\theta) + \cdots, \tag{4}$$

$$\frac{u(r,\theta)}{\alpha\varepsilon_0} = \left(\frac{J}{\alpha\varepsilon_0\sigma_0 I_n}\right)^{n/(n+1)} r^{1/(n+1))} \tilde{u}^{(0)}(\theta) + \frac{Q}{(J/\sigma_0)^t}\left(\frac{J}{\alpha\varepsilon_0\sigma_0 I_n}\right)^{(n-1)/(n+1)} r^{s(n-1)+t+1} \tilde{u}^{(1)}(\theta) + \cdots, \tag{5}$$

where J is Rice's J-integral, Q is a dimensionless constant that controls the magnitude of the second stress term

$$\tilde{\varepsilon}_{ij}^{(0)} = \frac{3}{2}\tilde{\sigma}_{ij}^{(0)^{n-1}} \tilde{s}_{ij}^{(0)}, \qquad \tilde{\varepsilon}_{ij}^{(1)} = \frac{3}{2}\tilde{\sigma}_{ij}^{(0)^{n-1}}\left[\tilde{s}_{ij}^{(1)} + \frac{3}{2}(n-1)\frac{\tilde{s}_{kl}^{(0)}\tilde{\sigma}_{kl}^{(1)}}{\tilde{\sigma}_e^{(0)2}}\right], \tag{6}$$

$$I_n = \int_{-\pi}^{\pi}\left[\frac{n}{n+1}\tilde{\sigma}_e^{(0)n+1}\cos\theta - n\tilde{\sigma}_{ij}^{(0)}\left(\frac{1}{n+1}\tilde{u}_j^{(0)}\cos\theta - \frac{d\tilde{u}_j^{(0)}}{d\theta}\sin\theta\right)\right]d\theta \tag{7}$$

and $n_1 = \cos\theta$ $\qquad$ $n_2 = \sin\theta$ $\qquad$ $s = -1/n+1)$ $\qquad$ (8)

Reference [18] provides numerical solutions for ι in terms of n, $\sigma^{(0)}$, $u^{(0)}$, $\sigma^{(1)}$ and $u^{(1)}$ for the plane strain state. For the state of plane stress, the second order stress component of $\sigma^{(1)}$approaches infinity as $\theta \rightarrow 160^\circ$ and thus the second order solution probably is not separable [18]. In the region of $\theta < 140^\circ$, however, $\sigma^{(1)}$ variation is normal and thus one can speculate that the two parameter stress expression holds within this restriction. This hypothesis is important if the two-parameter J-Q and J-T theories are to be used in characterizing ductile fracture of modestly thin plates where a 100 percent shear lips is anticipated. In the following, the adequacy of such two-parameter characterization is investigated by comparing the experimentally determined crack tip displacement fields in thin plate specimens with that predicted by the J-T and J-Q theories.

EXPERIMENTAL PROCEDURE

Details of the experimental procedure are given in [5] and thus only a brief summary is provided in the following.

Simultaneous vertical and horizontal displacements in uniaxially and biaxially loaded 2024-0, 2024-T3, 2091-T3 and 5052-H32 aluminum, cruciform and single-edge notched plates were determined by moire interferometry. Figure 1 shows the uniaxial and biaxial specimens which were loaded in a special testing machine. Uniaxial stress-strain relations in the vertical and horizontal directions of the aluminum alloy sheets were also determined and the average of the vertical and horizontal relations, which at the most differed by 5 percent, were used to fit the Ramberg-Osgood relation of Equation (1).

A scanning and digitizing routine was then used to compute the three strain components from the recorded moire fringes. Using the inverted form of Equation (1) to compute the stresses and hence the strain energy density and the resultant surface tractions along integration contour, the J-integral values along given rectangular contours, which encircle the crack tip, were computed. The J-integral value was then back substituted into Equation (5) to recompute the HRR displacement component or the first term in Equation (5). The second term, or the Q displacement component, was obtained by subtracting the HRR displacement component from the measured crack tip displacement or from the difference between the lefthand side and the first term in the righthand side of Equation (5). The resultant Q-displacement component versus radial distance, r, was then plotted on a log-log scale in order to verify the existence of the $r^{s(n+1)+t+1}$ component in the two orthogonal displacement components of the J-Q theory. If this second order term follows the same trend of that of the state of plane strain, then the component perpendicular to the crack should be an order of magnitude smaller than that parallel to the crack.

For the J-T theory, the second order displacement component varies with r and the perpendicular component should differ with the parallel component by the Poisson' ratio, ν.

RESULTS

Figure 2 show typical moire interferometry fringe patterns corresponding to the displacements parallel, u (= u_1), and perpendicular, v (=u_2), to the crack, respectively of a 2024-0 aluminum, single edged notch specimen. Also shown in Figure 2 are the rectangular contours used for J-integral calculation. Table 1 shows the expected power of r for Q-component of the u_i displacements of Equation (5).

Figures 3a and 3b show the variations of J values with crack extension or the J-resistance (J_R) curves for all 2024-0 and 2024-T3 cruciform specimens, respectively, which were subjected to uniaxial and biaxial loadings of $B = \sigma_{11}/\sigma_{22} = 0$ and 2, respectively. The theoretical J_R value for this series of tests was computed by assuming that the cruciform specimens can be modeled by the corresponding SEN specimen, also shown in Figure 1, and then by following the estimation procedure as outlined in [4] using the numerical constants of [10]. The purpose of the SEN modeling was to assess the influence on the measured J_R curves due to the added rotational constraint of the cruciform specimen. Despite this added constraint, the difference between the theoretical and experimental J_R curves is equivalent to that observed in the SEN specimens [2], thus underscoring the inadequacy of the theoretical estimation procedure.

Figure 4a shows the increase in the measured (identified as moire Exp) and the computed v displacement component, which is the first term in Equation (5), with crack extension. This v displacement component was computed by back substituting the measured J values into the first term of Equation (5) as described previously. Also shown is the elastic u-displacement computed by setting $J = G = K^2/E$ and then the crack tip displacement based on linear elastic fracture mechanics (LEFM). The good agreement between the measured and computed v indicates that the HRR field is a reasonable representation for the displacement component perpendicular to the crack.

Figure 4b shows the increase in the measured and the computed HRR u-displacement component, which again corresponds to the first term in Equation (5), with crack extension. Contrary to the results in Figure 4a, the difference in the computed HRR and the measured u progressively increases with crack extension. In this case, the HRR displacement does not agree with the measured u-displacement for uniaxial loading (B = O) but is in agreement with those of biaxial loading (B = 2) for a short crack extension of $\Delta a < 0.5$ mm. Thus the HRR component of the u-displacement field is not a valid representation of the measured crack tip u-displacement field.

Figure 5a shows log-log plots of the measured v-displacement and the computed HRR and the Q components of the v displacements along the radial lines of $\theta = 15°$, $45°$ and $120°$ in terms of the radial distance from the crack tip, r, in a 2024-0 SEN specimen at a particular stage of loading. Since the measured v displacements and the HRR components of the v displacements nearly coincide, the Q component of the v cisplacements is an order of magnitude smaller and possibly within the error band of measurement.

Figure 5b shows the corresponding log-log plot of the measured u-displacement and the computed HRR and the Q components of the u displacement. The Q u-components are the same order of magnitude as the measured u displacement and the corresponding HRR components of the u displacements and varies approximately as $r^{-0.05}$ for $r > 1$ mm with the slope approaching zero as $r \rightarrow 0$. The negative exponent implies a corresponding Q-strain component of $r^{-1.05}$ which is a stronger singularity than the corresponding HRR-strain singularity of $r^{-0.92}$ and violates the basic premise of Equation (1). The predicted exponent of r from the J-Q theory is given in Table 1.

Figures 6a and 6b show a similar log-log plots of the v- and the u-displacements in a 2024-0 cruciform specimen. While the measured v-displacement and the HRR component of the v displacements are in reasonable agreement with each other, the differences in the measured u-displacement and the HRR component of the u-displacement is substantial. The negative exponent of r in the Q component of the u-displacement is consistent with the results in Figure 5b and contradicts the positive expenent as predicted in the J-Q theory.

DISCUSSION

The results of Figures 5a and 5b suggests that the two parameter characterization of ductile fracture by the J-Q theory could not be a valid criterion although the $\tilde{u}^{(1)}$, $\tilde{\varepsilon}^{(1)}$ and $\tilde{\sigma}^{(1)}$ functions are yet to be determined for the state of plane stress if the stresses are separable into functions of r and θ. The fact that the negative slope of the Q-component approached zero as the $r \rightarrow 0$ and sugggests that true functinal form of the second parameter is a hybrid of the simpler J-T theory without r variation and the negligibly Q component of the v displacement of the J-Q theory.

CONCLUSIONS

Limited experimental results involving the crack tip displacement fields in thin aluminum SEN and cruciform specimens show that neither the J-Q nor the J-T theories of ductile fracture are valid ductile fracture criteria which can be used in in the absence of constraint.

The widely used J-integral computation procedure, also, must be reinvestigated when constraint is lacking in the fracture specimen.

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Table 1. n and Exponents of r

	n	t	s = -1/(n+1)	s(n-1)+t+1
2024-0	4	0.033	-0.2	0.433
2093-T3	8	0.071	-0.111	0.293
2024-T3	11	0.068	-0.083	0.238
5052-H32	15	0.061	-0.063	0.186

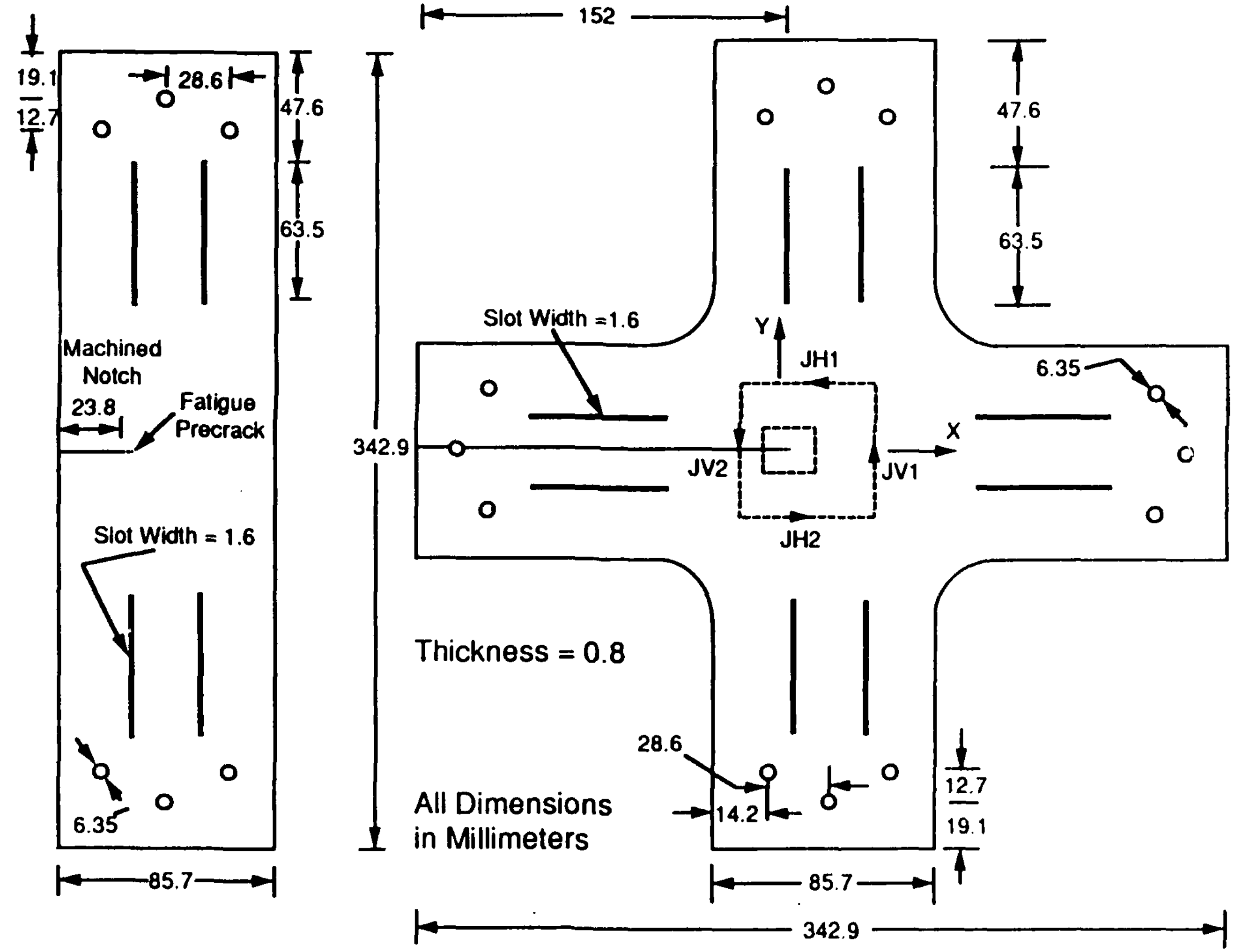

Figure 1. Cruciform and SEN aluminum alloy specimen

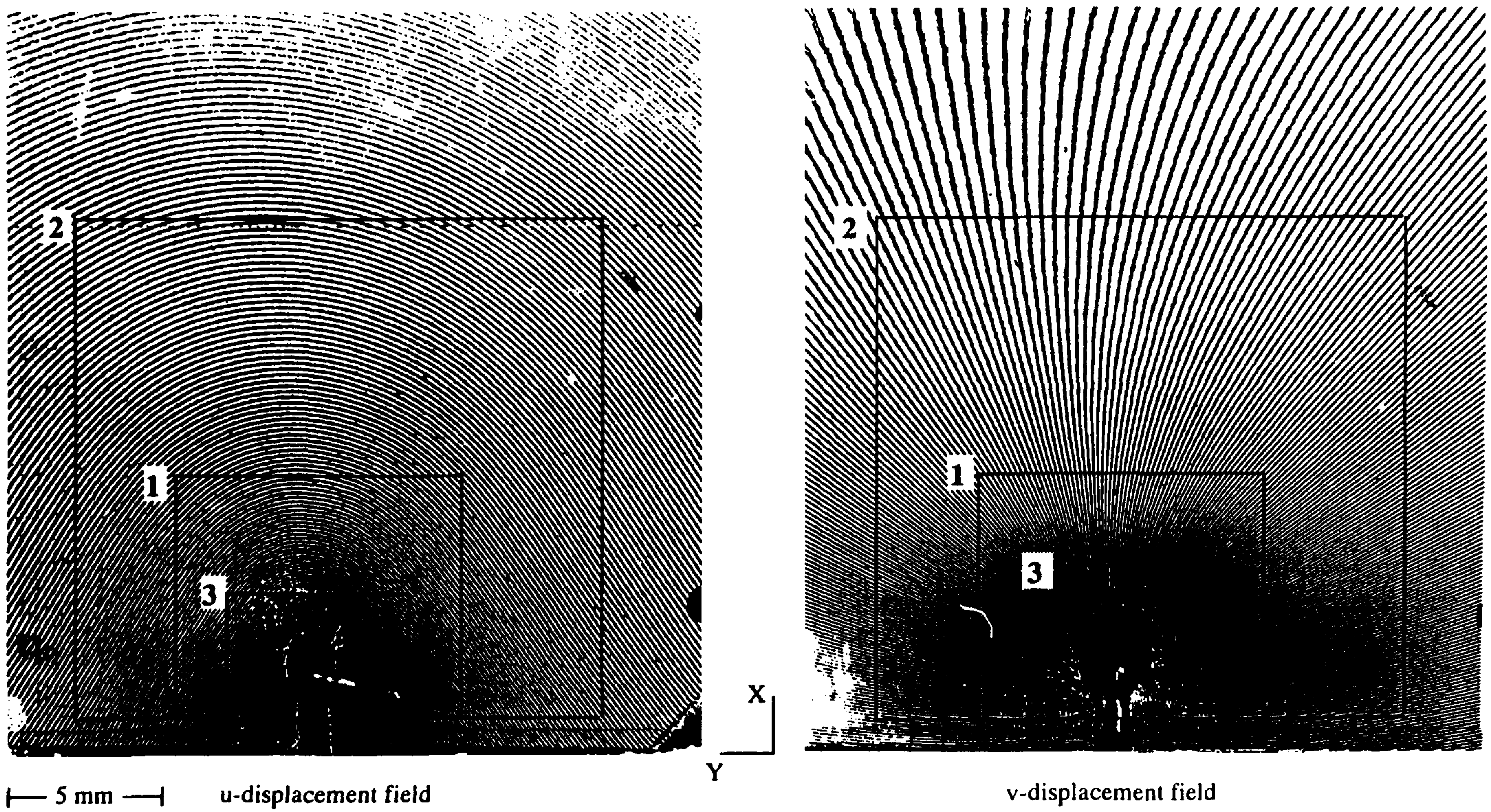

Figure 2. Moire interferometry patterns of a 2024-0 SEN specimen (J-integration paths shown in each figure).

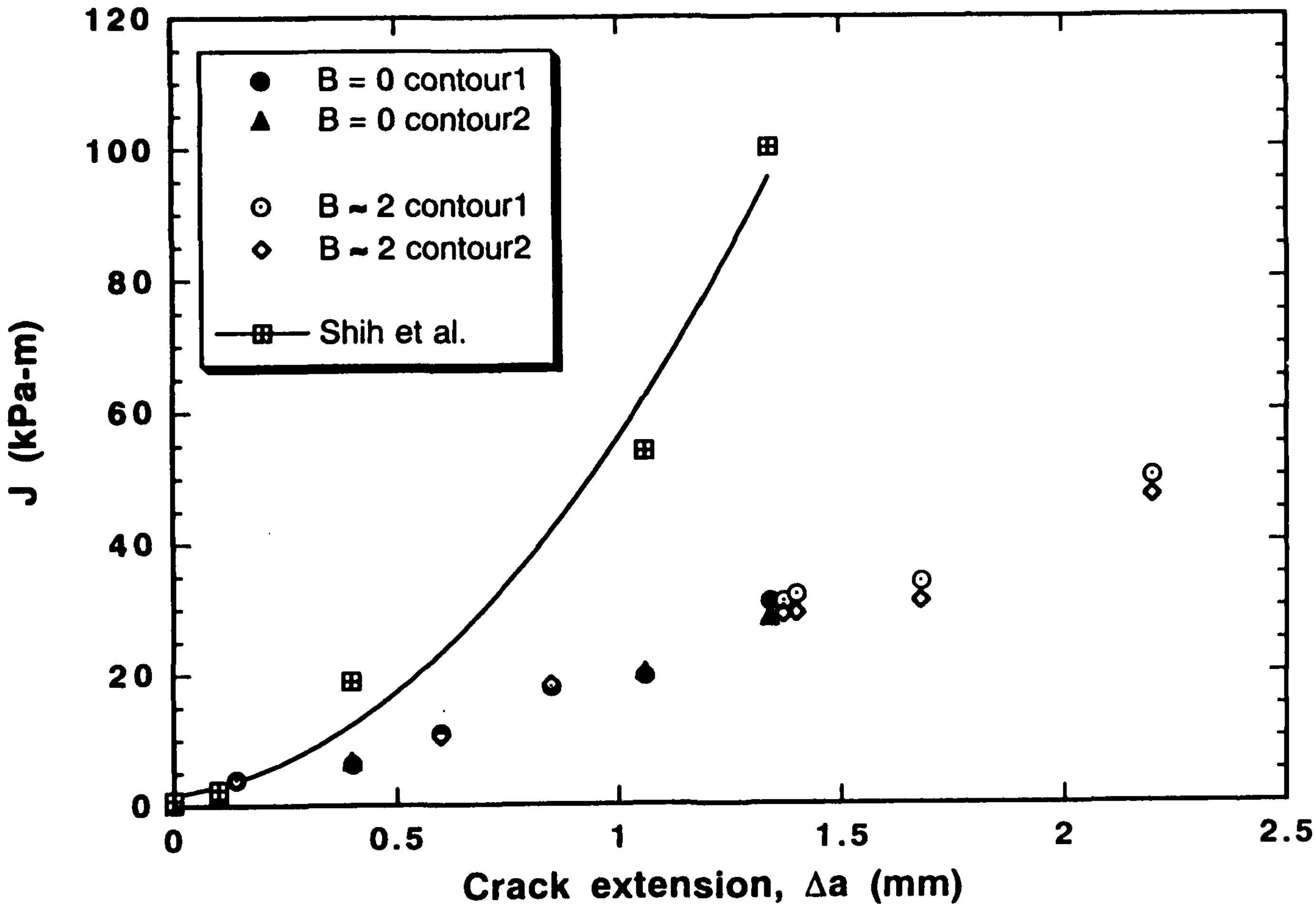

Figure 3a. J_R curves for all 2024-0 aluminum cruciform specimens. B is the biaxiality ratio.

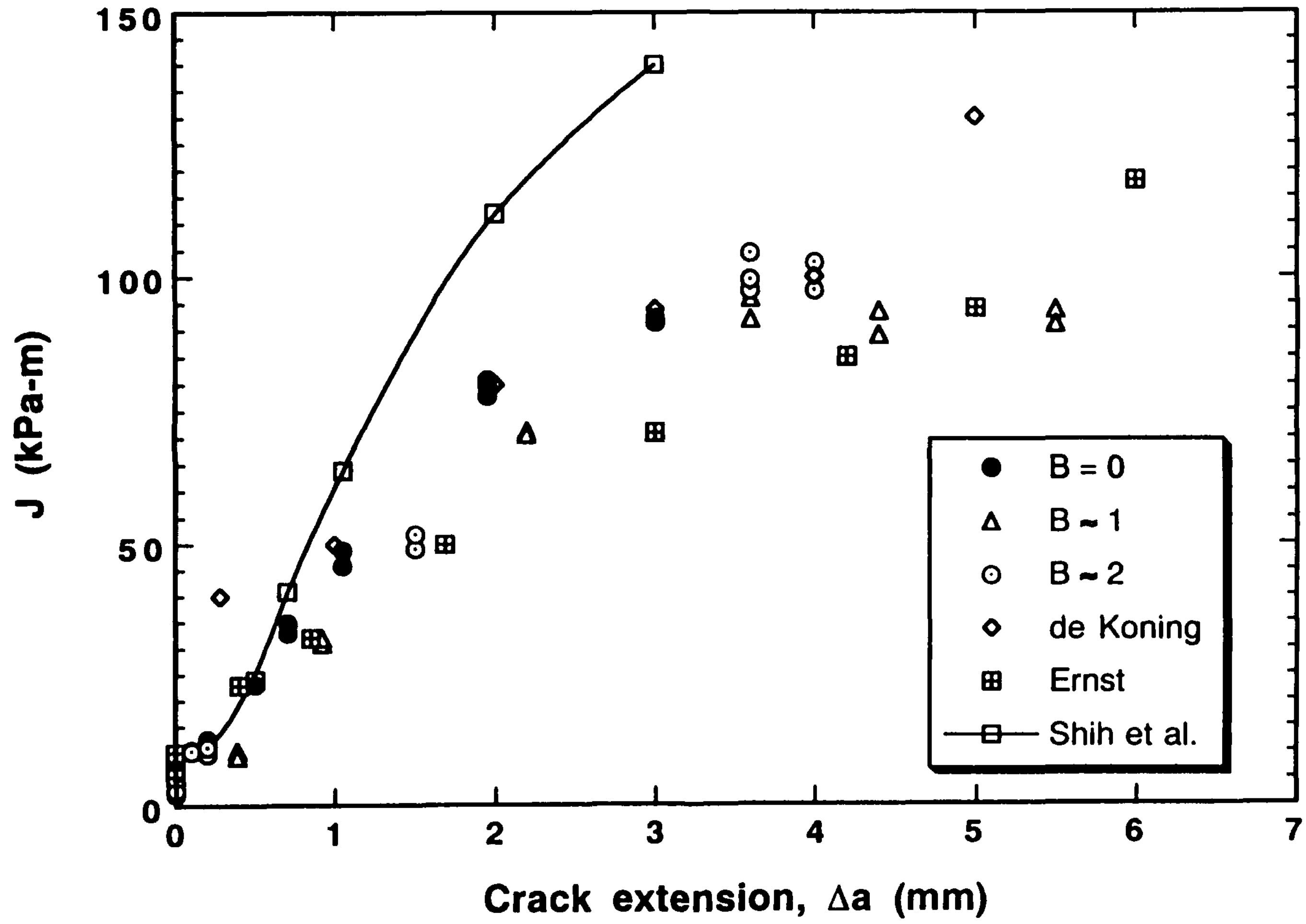

Figure 3b. J_R curve for all 2024-T3 aluminum cruciform specimens. B is the biaxiality ratio.

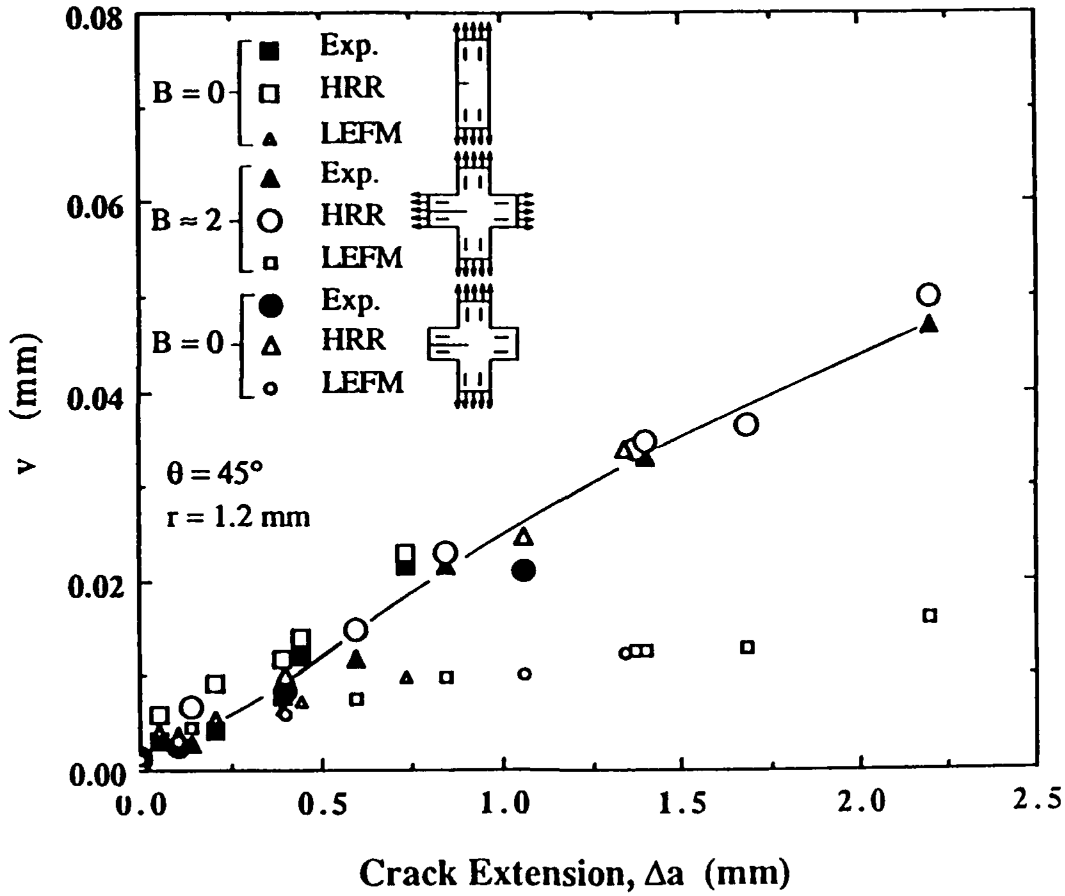

Figure 4a. v-displacement in 2024-0 aluminum, SEN and cruciform specimens. Data points represent measured v-displacement. Solid Curve represents the HRR component of v-displacement.

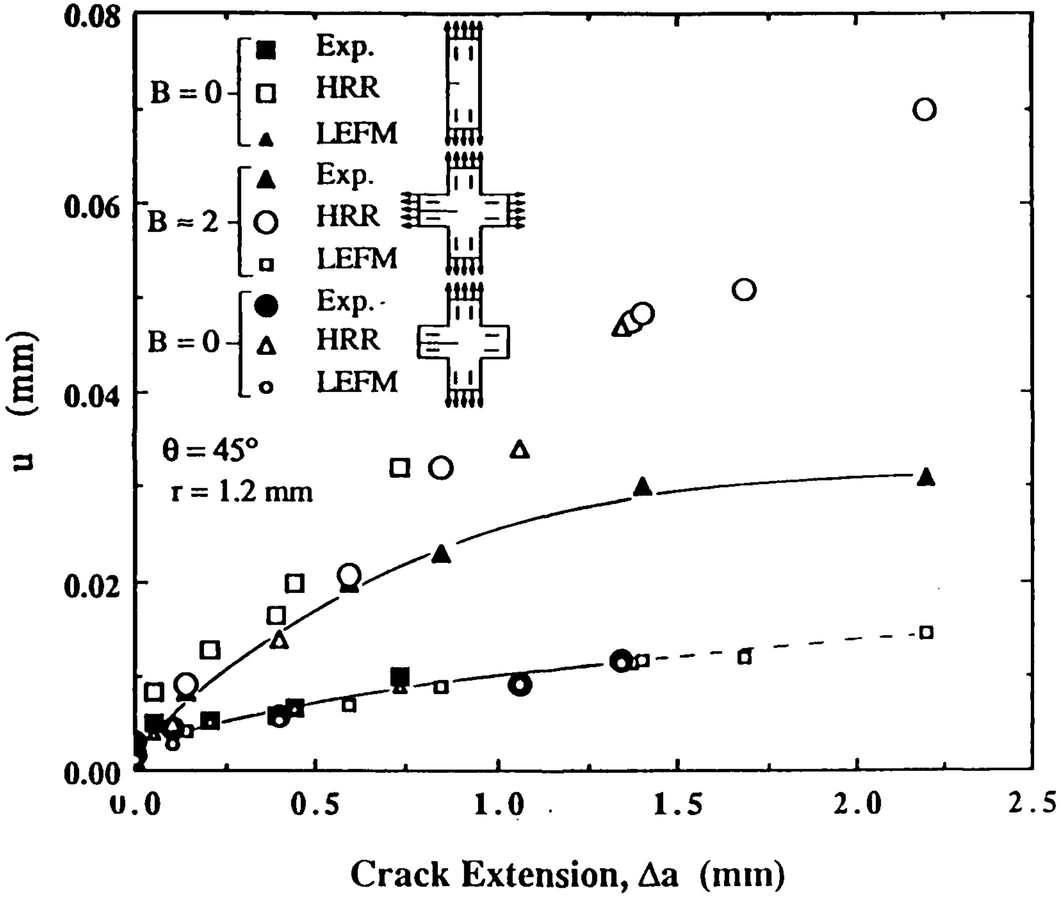

Figure 4a. u-displacement in 2024-0 aluminum, SEN and cruciform specimens. Data points represent measured u-displacement. Solid Curve represents the HRR component of u-displacement.

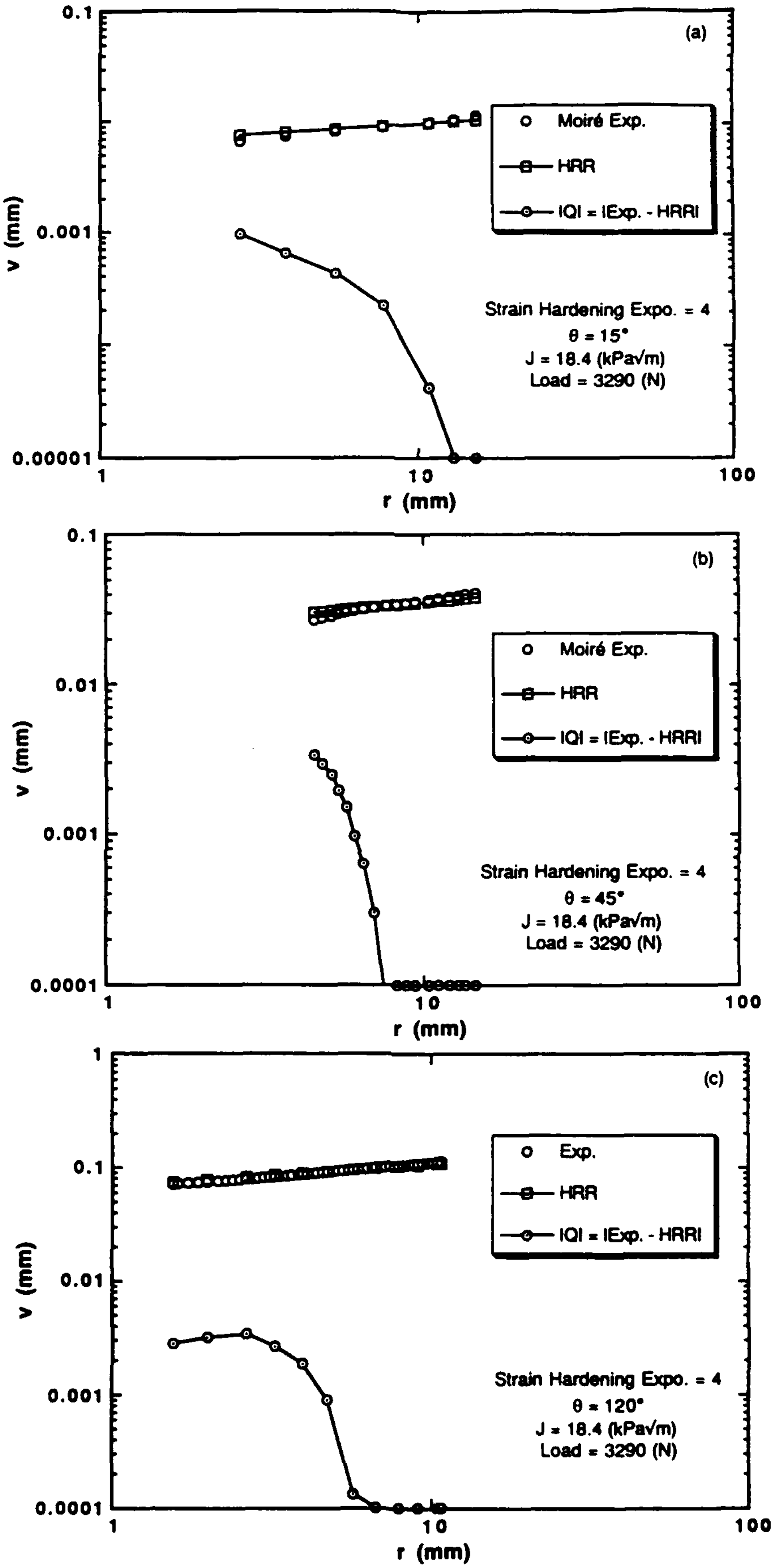

Figure 5a. v-displacement in a 2024-0 aluminum SEN specimen.

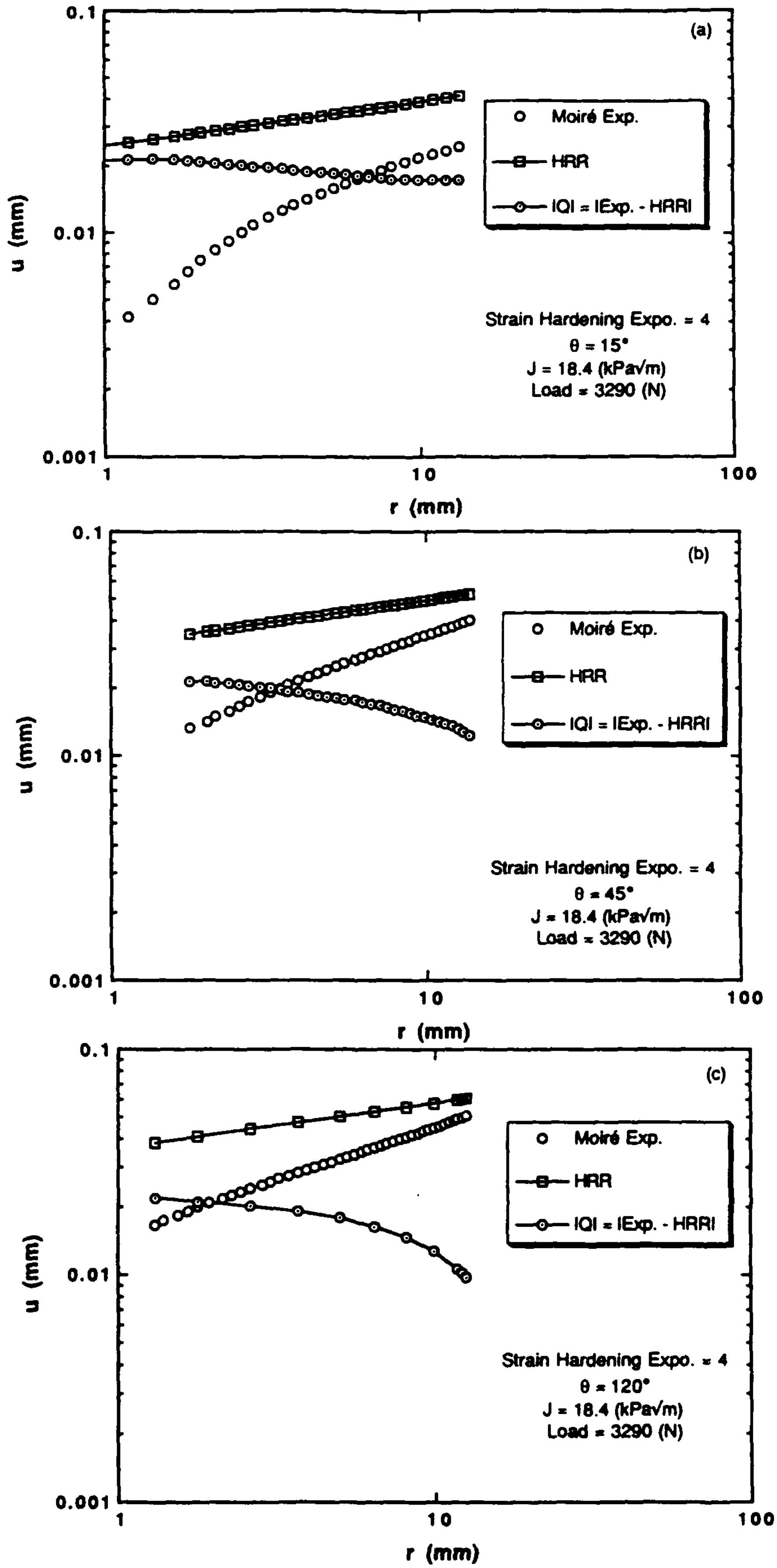

Figure 5b. u-displacement in a 2024-0 aluminum SEN specimen.

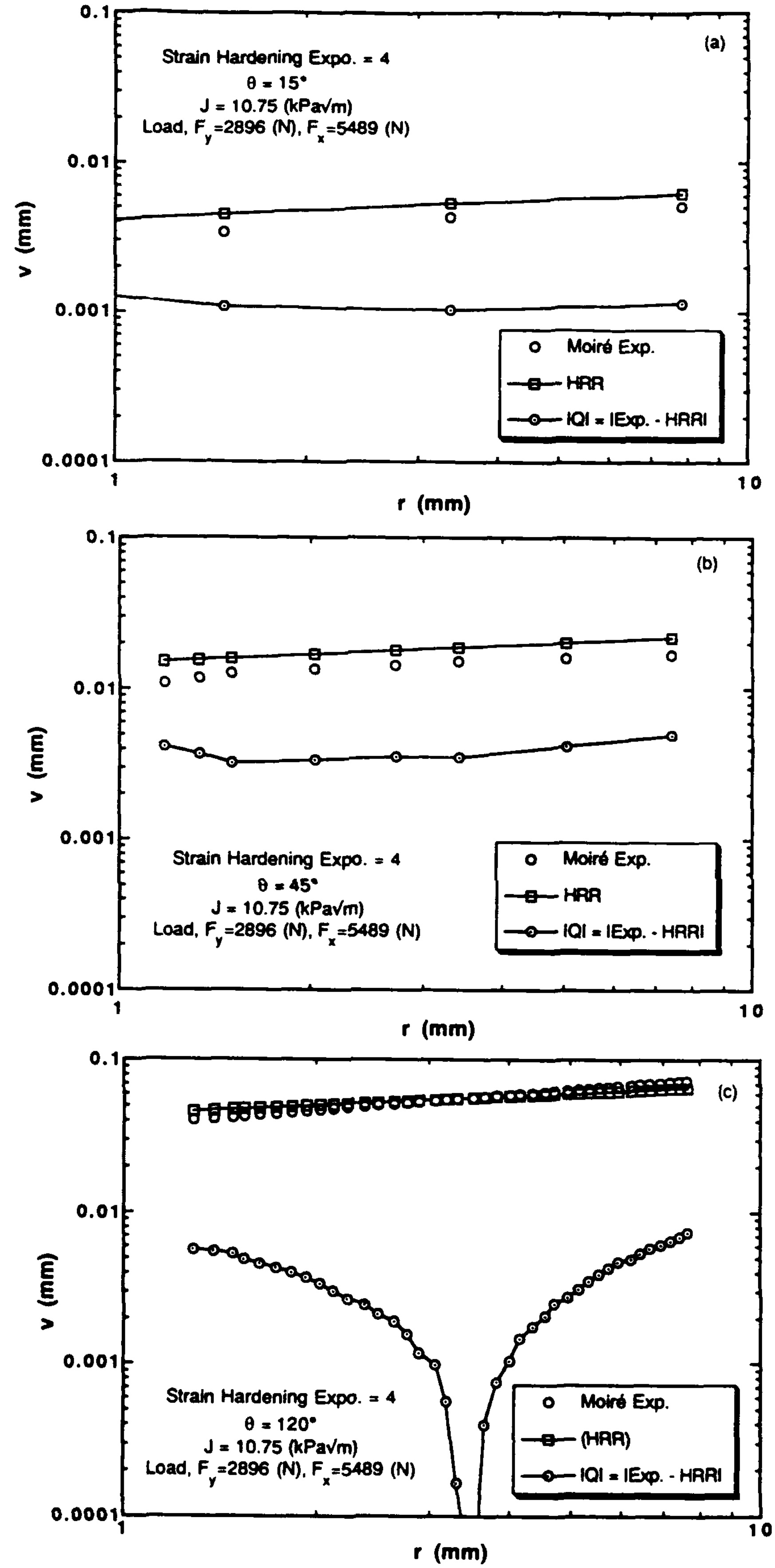

Figure 6a. v-displacement in 2024-0 aluminum cruciform specimen. B=2.

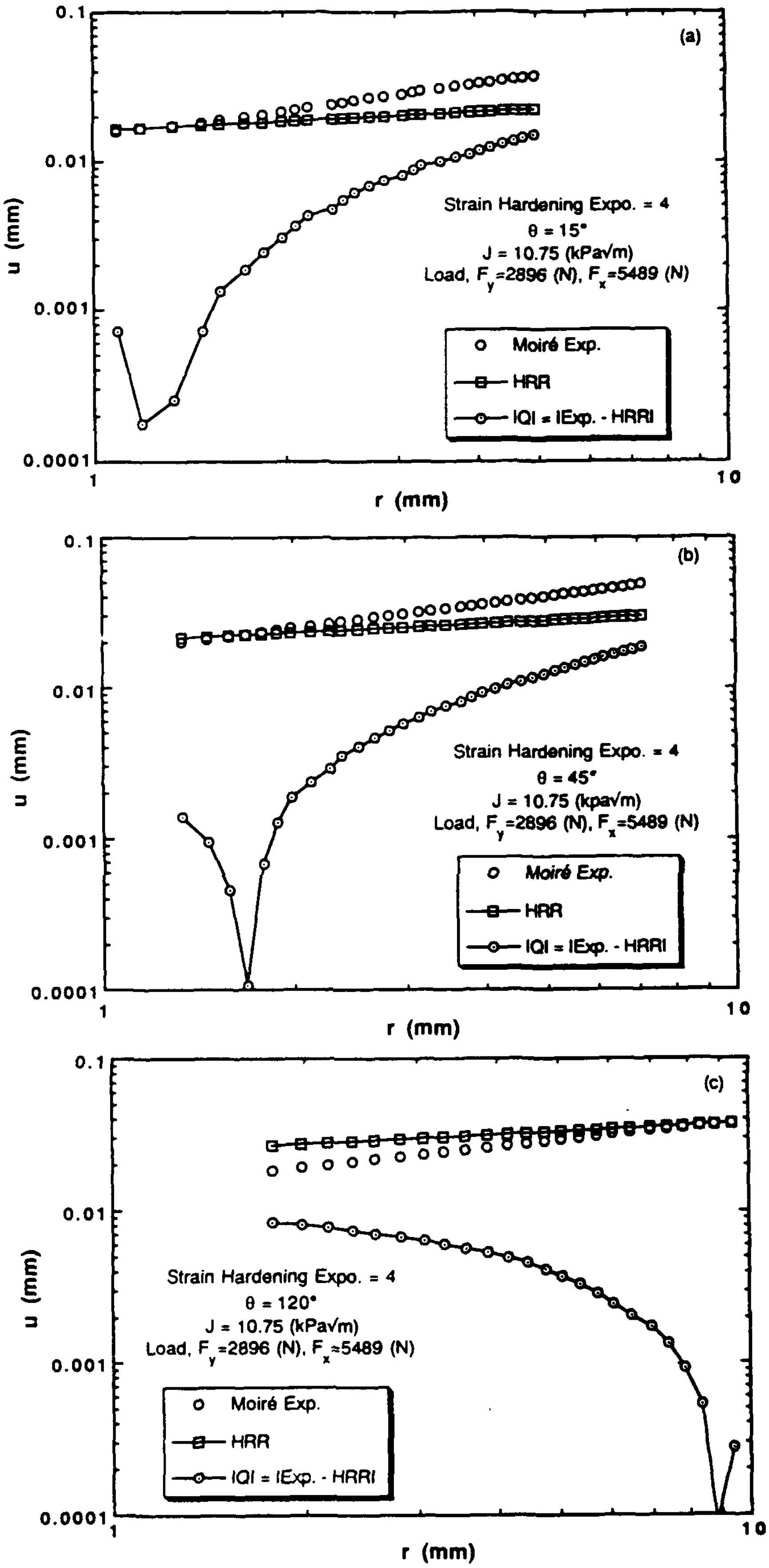

Figure 6b. u-displacement in 2024-0 aluminum cruciform specimen. B=2.

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20. ABSTRACT *(Continue on reverse side if necessary and identify by block number)*

J-integral values were determined directly from the measured orthogonal displacement fields surrounding a crack in 2024-0, 2024-T3, 2091-T3 and 5052-H32 aluminum alloy SEN and cruciform specimens of 0.8 mm thickness. These J-values were then used to compute the crack tip displacements associated with the HRR field. The second order displacement component in the two-parameter, J-T and the more general J-Q ductile fracture theories was obtained by subtracting the HRR displacement from the measured crack tip displacement. This second order displacement component

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